

STPSat-1: A New Approach to DoD Experiment Spaceflight

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Abstract. For small satellites, finding affordable access to space is a daunting hurdle. The Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) promises to make excess capacity on future EELV launches available for the Department of Defense (DoD) Space Test Program (STP) and other organizations as a lower-cost launch alternative. STP Satellite Mission 1 (STPSat-1) is the first STP satellite built specifically to exploit this capacity.

STPSat-1 continues STP's mission to provide access to space for DoD sponsored experiments. This spacecraft hosts four such experiments: Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER); Computerized Ionospheric Tomography Receiver in Space (CITRIS); Micro-Electro-Mechanical System (MEMS)-based PicoSat Inspector (MEPSI), and; Wafer Scale Signal Processing (WSSP). Consistent with STP's mission, these experiments will demonstrate new technologies for space applications.

This paper discusses several technical challenges being overcome by the STPSat-1 team. SHIMMER is the primary driver for spacecraft attitude and thermal performance. ESPA restrictions tightly constrain volume and mass. Limited knowledge of the launch environment exists since Delta IV has not yet flown (at this writing).

This paper will discuss the approach used to meet these technical challenges, present organizational structures used to optimize communications, and address design-to-cost and mission risk constraints.

Introduction

Engineering is the application of scientific knowledge to solve problems. The ability of the engineering community to solve any particular problem is a function of the state of advancement in technology and the availability of funds and other resources to dedicate to the task. There is never a single, unique, unambiguous solution to any engineering problem. The first determinant of the solution is the definition of the problem (and the requirements). The second determinant is the selection of optimization parameters. Every potential solution can be evaluated with respect to specified optimization parameters. The final solution is shaped by the parameters selected for optimization and their weighting.

In these respects, STPSat-1 is typical of all engineering projects. The design that has been developed is a function of the requirements as well as the optimization parameters. Stated generally, two requirements drive the STPSat-1 design: 1) satisfy the requirements of the selected

payloads (e.g., pointing, thermal, power, etc.), and; 2) develop a system that is compatible with the existing interfaces (launch vehicle, communications, mission operations, etc.). Two optimization parameters complete the definition process: 1) stay within the cost envelope, and; 2) minimize technical risk. Figure 1 shows how all of these constraints have affected the ultimate STPSat-1 design.

STPSat-1 Mission Overview

Space Test Program Background

STP is an organization charged with providing flight opportunities for DoD research and development experiments. The executive management of the program falls to the United States Air Force (USAF) and is administered by the Space and Missile Systems Center Detachment 12, Space Test Program Office (SMC Det 12/ST) at Kirtland Air Force Base. The STP Director is Col. Richard W. White, Jr. The STP Office has three major divisions. The Mission Design and Management Division is the front door for experiments entering STP, performing initial mission planning and

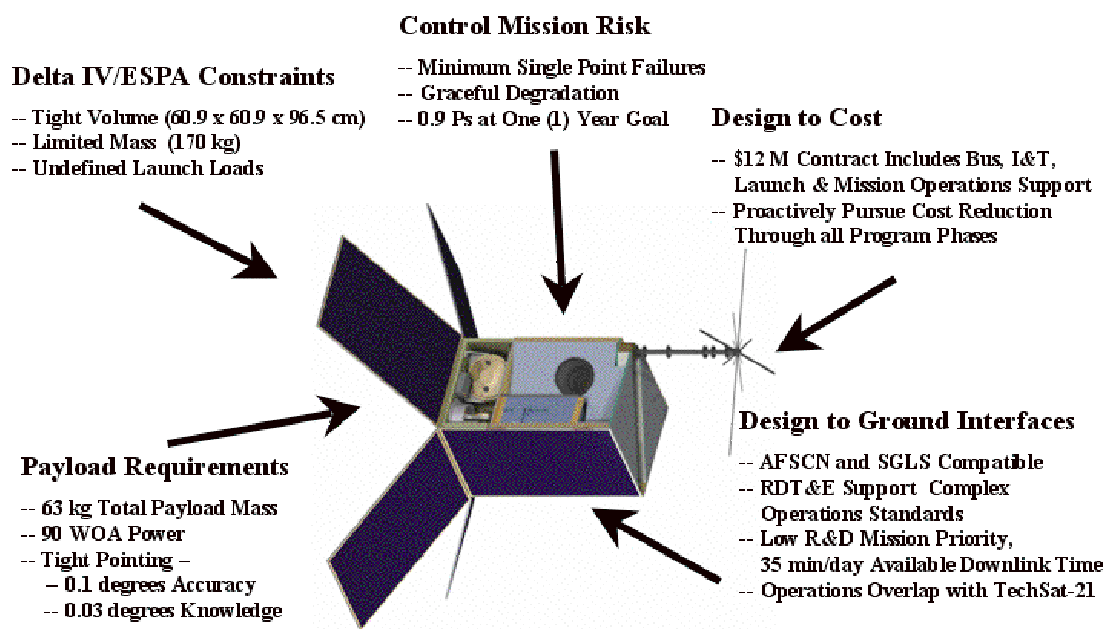


Figure 1. The STPSat-1 Spacecraft Design is Driven by Many Challenging Constraints

assignments. The DoD Shuttle/ISS Payloads Division is responsible for STP missions involving the Space Transportation System (Space Shuttle) or the International Space Station (ISS). The Tri-Service Missions Spacecraft Division is responsible for STP missions procuring spacecraft to host experiments. It is the last of these three that is executing STPSat-1.

The focus of STP is not to develop experiments. Instead, working from a list of DoD-sponsored experiments provided by the Space Experiments Review Board (SERB), STP functions as a broker to get as many SERB experiments on orbit as possible within STP's budget constraints, in as timely a manner as possible. For a more complete description of the process for approving and manifesting an STP experiment, see Sims and Zdenek. SERB experiments that successfully make it to orbit contribute directly to operational systems that support the warfighter - in fact, many current operational systems trace their pedigrees directly to past STP missions.

STP is constrained primarily by budget, a large portion of which must be allocated to sustaining launch costs. Like all elements of the space community, STP is always looking for ways to reduce launch costs for its missions. This universal issue of disproportionate launch costs motivates the current effort to utilize excess capacity of the EELV. ESPA, which is designed to carry up to six small (181 kg) satellites, has the potential to new opportunities for orbiting small satellites for STP, and potentially for other organizations. (For an overview of ESPA, see Wegner, Ganley and Maly).

Organizations, Roles and Responsibilities

Multiple organizations are involved in providing mission hardware and services for STPSat-1 throughout the mission lifetime. Table 1 summarizes the organizational elements of STPSat-1 and describes their roles and responsibilities.

Program Management

Because mission teams are often geographically dispersed and travel funds are very limited, STP

Table 1. STPSat-1 Organizations and Their Roles and Responsibilities

Organization	Roles and Responsibilities
USAF Space Test Program (SMC/Det-12/ST)	Overall Mission Management for STPSat-1 and Mission Management for the MLV-05 launch vehicle
AeroAstro, Inc.	Prime contractor for STPSat-1 spacecraft bus, experiment integration, system test, launch vehicle integration, mission operations support (AeroAstro is supported by subcontractors in critical roles, including TASC for system engineering and quality assurance and Avidyne Corporation for Attitude Determination and Control Subsystem development).
Experiment Providers: • Naval Research Lab (SHIMMER and CITRIS) • Air Force Research Lab (WSSP and MEPSI)	Provide flight-ready experiment hardware and software for integration with the spacecraft bus; support space vehicle system test program; support experiment mission operations through STPSat-1 mission life
SMC/Det-12/VO	Mission Operations responsibility including pre-launch planning, testing, and rehearsals, and conducting complete post-launch mission operations using the RDT&E Support Complex (RSC) and the AFSCN network
Integrating Contractor (Selection in JUN 02)	Serves as the integrator for the primary and secondary payloads for the MLV-05 launch; generates all pre-launch documentation, provides range interface, integrates hardware on the Delta IV and ESPA ring prior to launch. Source selection for this contractor by STP is in process at this time.

makes extensive use of Integrated Product Teams (IPTs) to manage the STPSat-1 program. The STPSat-1 team holds weekly Operations, Payload, Program Management, and Spacecraft IPTs via teleconference. Launch Vehicle IPTs are held on an as-needed basis at this early juncture of the program, but will become weekly as the mission progresses towards launch. These IPT meetings keep the team in communication and ensure that current issues remain in the fore, requiring a minimum of face-to-face time. Descriptions of the functions of each IPT follow.

The Operations IPT, attended by STP, the operations team, the PIs, and the AeroAstro SV engineering team, is held to discuss all operations issues. This IPT focuses on developing the Operations Concept in the early stages of the program and stresses mission operations readiness as launch approaches. The Payload IPT, attended by STP, the PIs, and the AeroAstro SV engineering team, focuses on experiment accommodation and experiment-to-spacecraft interfaces. The Program Management IPT, attended by STP and AeroAstro management, focuses on programmatic issues. The Spacecraft IPT,

attended by STP, the AeroAstro SV engineering team, and ad hoc Aerospace support, meets to update the program office on spacecraft development and to focus on spacecraft subsystem issues. The Launch Vehicle IPT, attended by STP, the LV provider, the integrating contractor, and the AeroAstro SV engineering team, discusses LV-to-SV interfaces and other LV-imposed requirements on the SV.

All action items generated on the STPSat-1 program are assigned to the appropriate IPT for tracking, reporting, and closure. Action items are tracked by STP in a common, searchable database, and are reviewed weekly at the IPT meetings. In addition to IPT meetings, teleconferences are also frequently used for subsystem focus groups and Monthly Management Meetings. E-mail is used to track and formally close action items and for technical data exchange. In addition, AeroAstro hosts an FTP site on which they can store and disseminate design files for team review.

Program Schedule

A milestone schedule is included as Figure 2. The STPSat-1 program envisions a three-year development schedule (including several

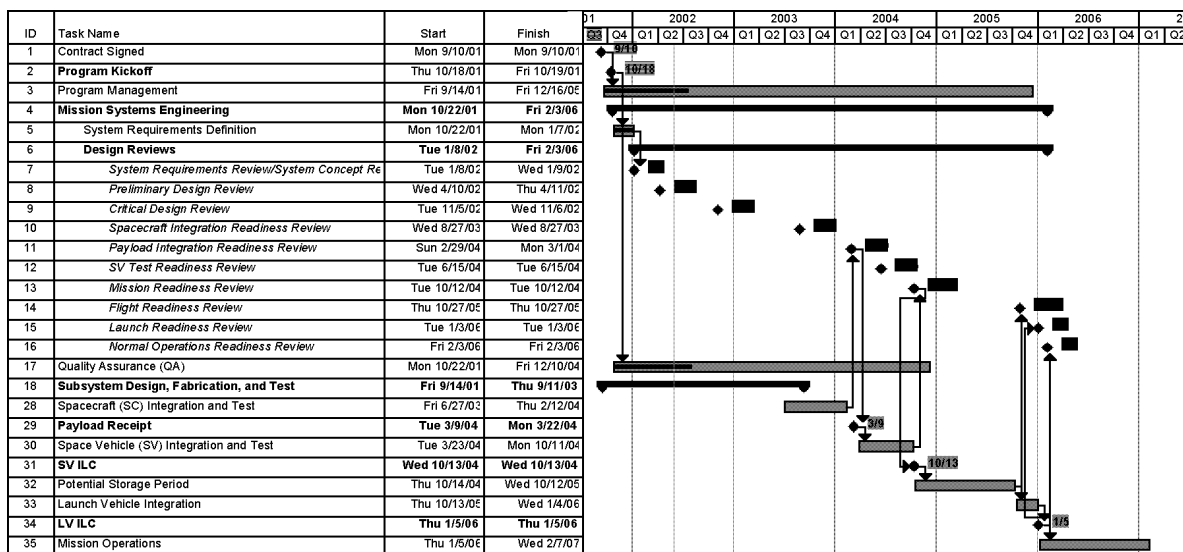


Figure 2. The STPSat-1 Program Anticipates a Storage Period of up to One Year

months of margin), with the space vehicle integrated, tested, and ready for shipment to the launch site in October 2004. The MLV-05 launch, however, is scheduled for the first quarter of 2006. STPSat-1 therefore faces a storage period of up to a year. STP chose to issue the bus contract relatively early to reduce MLV-05 launch schedule risk. The STPSat-1 experiments have varying degrees of design maturity ranging from SHIMMER, with previous flight history, to WSSP, which is a completely new design for space flight. In general, experiment design reviews must be completed before SV design reviews are conducted. At this writing, the STPSat-1 program anticipates SV Critical Design Review in November 2002.

Payload Instrumentation

STPSat-1 hosts four experiments selected by the SERB: Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER); Wafer

Scale Signal Processing (WSSP); Computerized Ionospheric Tomography Receiver in Space (CITRIS), and; Micro-Electro-Mechanical (MEMS)-based Pico Sat Inspector (MEPSI). The SERB-selected experiments are provided as Government Furnished Equipment (GFE) to AeroAstro. The STPSat-1 Principal Investigators (PIs) who are responsible for designing, building, testing, and delivering the experiments include scientists and engineers from the Naval Research Laboratory (NRL) for SHIMMER and CITRIS and the Air Force Research Laboratory (AFRL) for MEPSI and WSSP.

SHIMMER, the primary payload on STPSat-1, is a high-resolution ultraviolet spectrometer based on an optical technique known as Spatial Heterodyne Spectroscopy (SHS). SHIMMER, shown in Figure 3, will demonstrate that SHS facilitates the design of low mass, low power, low volume, and high throughput spectrometers for space-based remote sensing. SHIMMER will image the earth's limb at low latitudes,

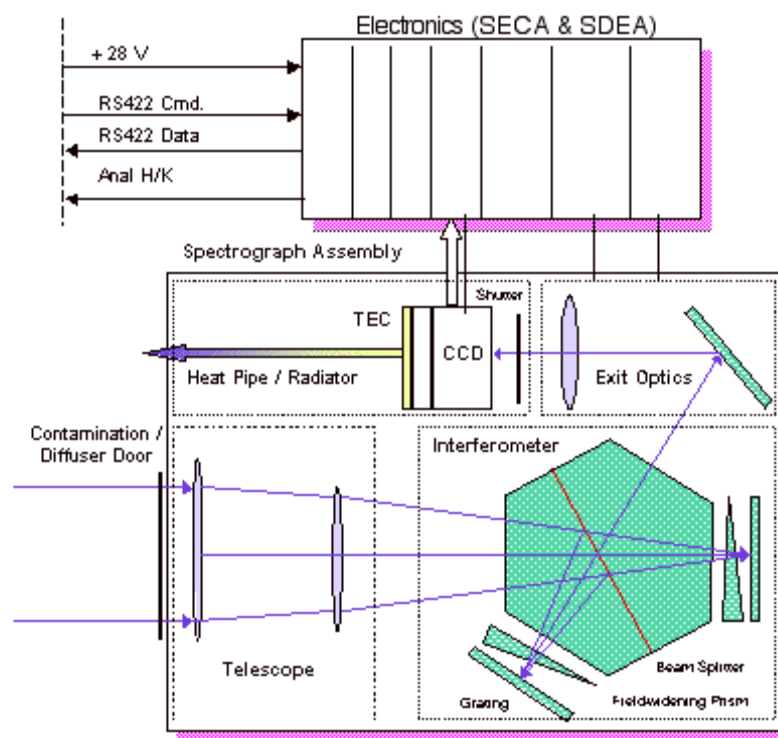


Figure 3. Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER)

measuring hydroxyl (OH) resonance fluorescence around 308 nm. These long-term global-scale measurements will contribute significantly to the small set of existing atmospheric OH observations. These observations will help to answer questions about the chemical and dynamic processes in the middle atmosphere, improving model validation and forecasting capabilities. As the primary payload, SHIMMER requirements are principal design drivers for STPSat-1.

WSSP, a secondary payload on STPSat-1, is a 6U Versa Module Europa (VME) circuit card built to demonstrate high-performance wafer-scale on-board signal processing on STPSat-1. WSSP, shown in Figure 4, will test the performance of a miniaturized signal processor in a radiation environment. Through wafer-scale packaging, four WSSP elements that dissipate 10 W and fit on a single 5 cm x 5 cm Multi Chip Module (MCM) can be stacked 4 high for a total volume of 16 cm³. This compact module provides processing at rates of up to 8 GFLOPS (Giga Floating-point Operations Per Second). The WSSP board (Figure 5) contains 3 versions of the WSSP MCM: one unshielded, non-radiation-hardened MCM; one shielded, non-radiation-hardened MCM,

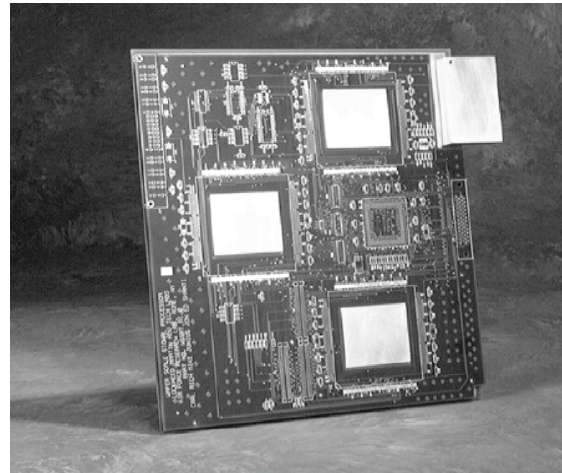


Figure 4. Wafer-Scale Signal Processor Board

and; one unshielded, radiation-hardened MCM. The PI will evaluate the performance of all three MCMs by processing sensor data (obtained from a camera mounted on STPSat-1) as well as a set of performance algorithms that measure radiation effects, fault tolerance, and image data processing capability. These results will be compared to results from an identical configuration undergoing radiation testing on the ground. WSSP also includes an antenna to receive telemetry from the MEPSI experiment, allowing WSSP to also process data from an independent sensor.

CITRIS (shown in Figure 5), another secondary payload on STPSat-1, is a tri-frequency receiver

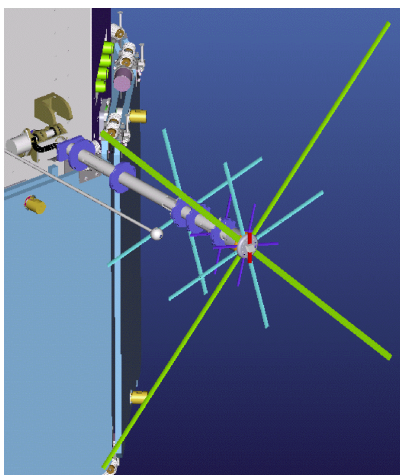


Figure 5. Computerized Ionospheric Tomography Receiver in Space (CITRIS)
(*deployed antenna and receiver units*)

utilizing a multi-band antenna located on STPSat-1. Beacons from the Coherent Electromagnetic Radio Tomography (CERTO) experiment located on other satellites are detected by CITRIS to provide satellite-to-satellite measurements of Total Electron Count (TEC) and propagation fluctuations. Occultation of the earth's ionosphere can be used to derive electron density profiles from these TEC measurements. CITRIS will also receive signals from ground-based radio beacons all around the world. The receiver will make both amplitude and phase measurements to provide scintillation data at Very High Frequency (VHF), Ultra High Frequency (UHF), and L-Band frequencies.

MEPSI, the third STPSat-1 secondary payload, contains a pair of MEMS-based PicoSats in a launcher that can eject these PicoSats from STPSat-1. The PicoSats can then be operated independently of STPSat-1 for approximately 24 hours. MEPSI (shown in Figure 6) will demonstrate an intelligent hardware agent that enables autonomous satellite operations. The highly integrated PicoSat bus, using MEMS-based

subsystems, will be a dramatic demonstration of low-power autonomous on-orbit capability. MEPSI will demonstrate the functional and dynamic interactions of MEMS-based subsystems which may include radio transceivers, 3-axis inertial sensors, micro-propulsion, magnetometers, imagers, range finders, data storage modules, health monitoring capabilities, data processing, power generation, and star/sun sensors. Operationally, MEPSI will demonstrate the capability to store a miniature (less than 1 kg) on-board agent that can be released on command to conduct surveillance of a host vehicle for independent situational awareness.

Launch Vehicle Selection

STPSat-1 will be one of five secondary SVs on the Medium Launch Vehicle 2005 (MLV-05) EELV mission. MLV-05 is an STP-executed mission to demonstrate the ESPA launch profile. Currently, the MLV-05 primary SV is the US Navy's Indian Ocean METOC Imager/Geostationary Imaging Fourier Transform Spectrometer (IOMI/GIFTS). Besides STPSat-1, the other secondary SVs include the three SVs comprising the AFRL's

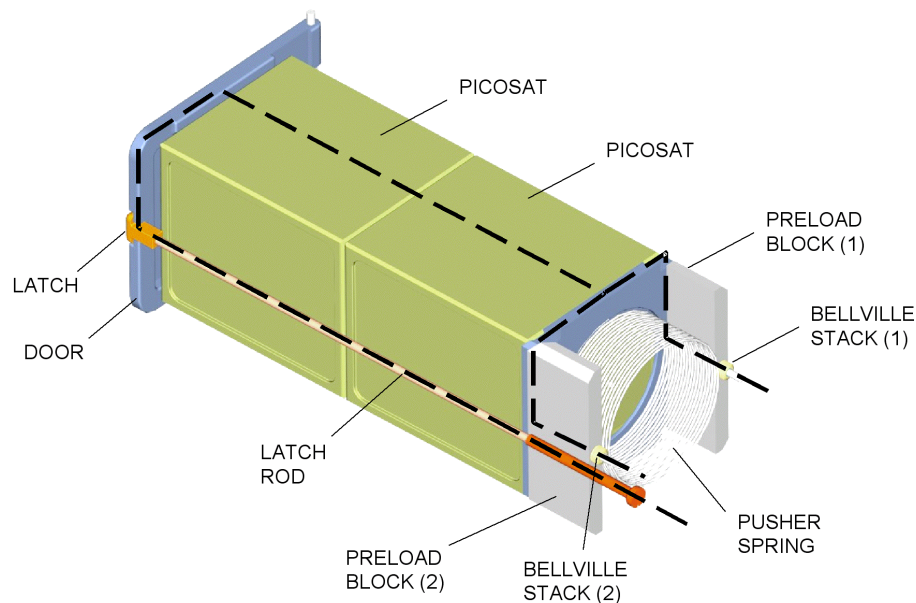


Figure 6. MEPSI Payload Launcher Assembly Housing Two PicoSats

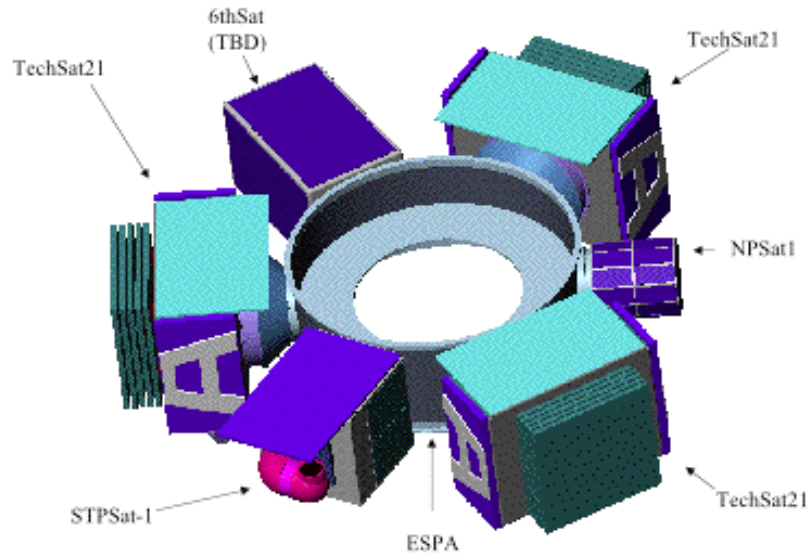


Figure 7. ESPA Configuration Showing MLV-05 Payload Complement
(Note: STPSat-1 is shown in a conceptual configuration pre-proposal)

Technology Satellite for the 21st Century (TechSat-21), and a contribution from the Naval Postgraduate School called NPSat-1. (For information on MLV-05, see Mocio). Figure 7 shows the MLV-05 configuration.

The MLV-05 mission will launch on a Delta IV-M EELV from Cape Canaveral Air Force Station in Florida. The expected launch date is in the first quarter of calendar year 2006. The Delta IV-M will first achieve the shared orbit for all of the secondary satellites (560 km altitude, circular, 35.4 degrees inclination) and will dispense all of the secondary satellites. The sequence timing will be driven by the need to avoid re-contact between satellites after deployment. After depositing the secondary satellites in their low-earth orbit, the Delta IV-M will inject IOMI/GIFTS into a Geostationary Transfer Orbit.

STPSat-1 as an ESPA Pathfinder

STPSat-1 is the next in a long line of missions procured to fulfill the STP mission of placing DoD experiments on orbit.

However, STPSat-1 also fills a unique role as the STP pathfinder for future ESPA payloads. The configuration of the ESPA system poses a number of real challenges for future missions that would exploit this important capability. STP has begun to study issues related to integration of SVs to the ESPA ring, given the minimal space that technicians will have when reaching the payload adapters of the primary and secondary SVs. Furthermore, each secondary SV will be mated to the ESPA ring cantilevered from its interface port, i.e., the normal of the ESPA interface plane will be perpendicular to the launch vehicle thrust axis (see Figure 8). It is not fully understood how



Figure 8. EELV Secondary Payload Adapter (ESPA)

this will affect dynamic environments. The size of the SV is such that the contribution of the acoustic environment to the overall dynamics load is ambiguous. Deployment from the ESPA with the primary SV attached and at least one secondary SV as a neighbor will demand careful planning and execution to ensure that secondary SVs separate in a reliable and controlled manner and do not endanger other SVs. If STP is to convince nervous owners of operational satellites to allocate excess capacity for ESPA missions, STP must answer all of the questions that these challenges pose.

The MLV-05 mission imposes yet another constraint: on the STPSat-1 project cost. The ESPA demonstration flight is of critical importance to STP to gain future capability, and thus demands STP's funding and attention. STPSat-1 is funded using residuals from the budget for the MLV-05 mission at large. Therefore, STPSat-1 is a

design-to-cost mission. The funding available for the STPSat-1 prime contract was \$12M, as stated in the initial AF procurement documentation.

By planning and executing STPSat-1, STP will gain first-hand experience with the issues inherent in designing and building an SV to be launched from the ESPA ring. Not only with this experience help STP answer questions from potential "capacity donors," STP will begin to acquire experience with this unique launch mode - experience that can be passed on to the small satellite community to take advantage of ESPA opportunities.

STPSat-1 Space Vehicle Overview

The PDR-level design configuration of STPSat-1 is presented in Figure 9. The vehicle is divided into two modules, the Avionics Module and the Payload Module.

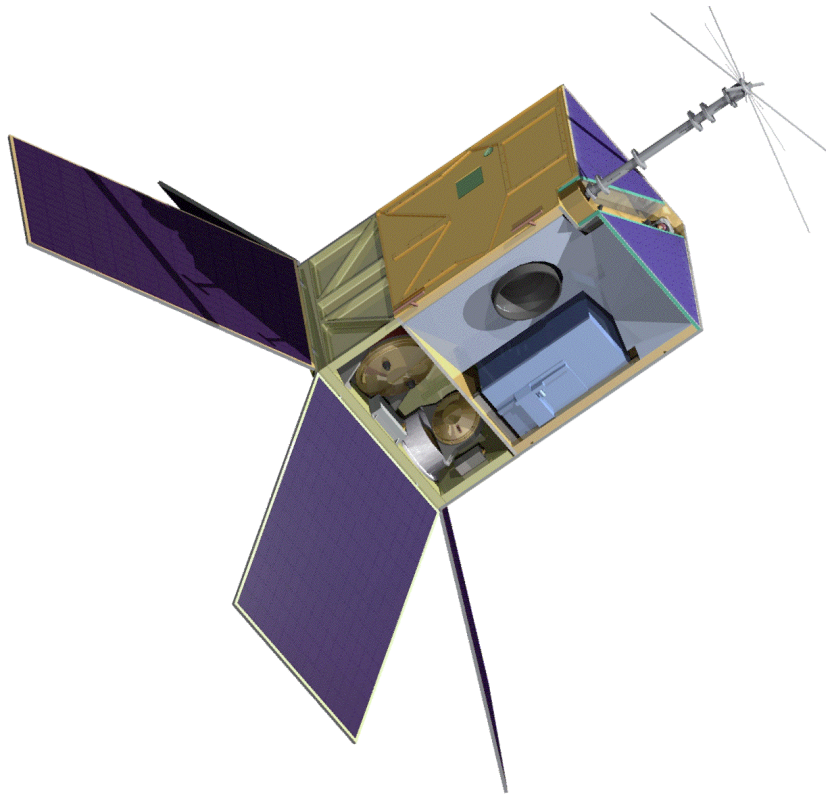


Figure 9. The STPSat-1 Vehicle

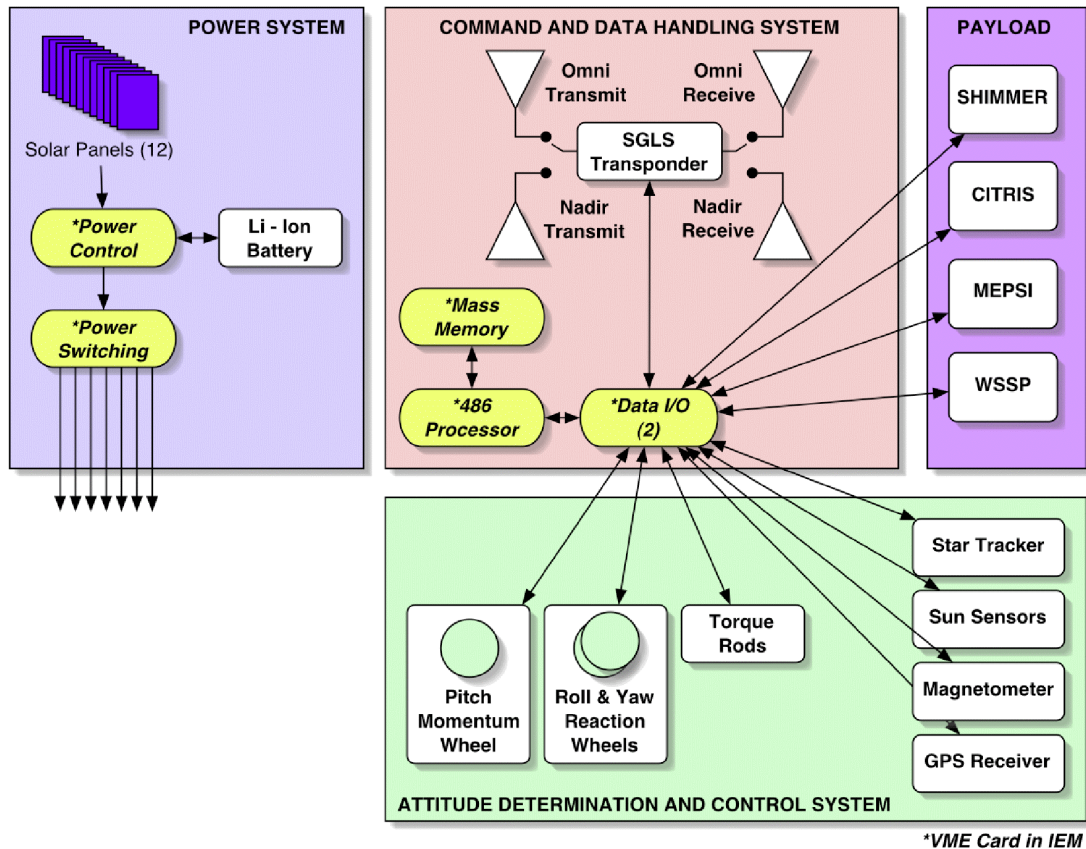


Figure 10. STPSat-1 Block Diagram

A top-level block diagram of the SV components is shown in Figure 10. The majority of the bus avionics are contained in a single box, the Integrated Electronics Module (IEM). Further design details are discussed in subsequent sections.

STPSat-1 Design Challenges

Designing to Payload Requirements

The STPSat-1 spacecraft exists to support its four experimental payloads. The Mission Requirements Document (MRD) contains both payload-specific and common requirements that the spacecraft bus must support. These requirements are the primary drivers in the SV design.

The four payloads on STPSat-1 perform significantly different types of experiments

and each requires unique accommodations from the bus. The primary instrument, SHIMMER, needs accurate alignment to the SV coordinate system, precise SV pointing knowledge and control, an unobstructed field of view, and tight thermal control. CITRIS requires an unobstructed hemisphere around its multi-frequency antenna and an electromagnetically pristine environment in its bands of operation. WSSP dissipates significant levels of power in a small volume and has an imager and antenna that require unobstructed fields of view. Although MEPSI is active only at the end of the mission (and even then only for a short duration), it requires an unobstructed trajectory surrounding the nominal PicoSat ejection path. The three experiments that are active throughout the mission (SHIMMER, CITRIS, and WSSP) have moderate power draws, however, they operate simultaneously during much of the mission and the aggregate sum of their power

consumptions can be up to 52% of the SV's total orbit average power consumption.

The SV will meet the stringent attitude determination and control requirements (0.5 degree control, 0.03 degree knowledge) by implementing a 3-axis stabilization system using a star tracker to determine absolute SV attitude. The payload requirements allow for a system that is momentum-biased about the pitch axis. A momentum wheel is used to maintain nadir-pointing attitude, while two smaller reaction wheels provide off-axis adjustments and special attitudes as needed. This configuration allows the SV to point the SHIMMER field of view to a tangent point 21.5 degrees below the orbit normal and at least 90 degrees from the ram direction as required, point the CITRIS antenna in either the ram or wake direction as required, and point the WSSP camera toward nadir. Special attitudes needed to calibrate SHIMMER (involving pointing toward the moon) can be accommodated as needed. The star tracker is the primary reference for attitude determination during normal operations, but additional sensors are utilized. As magnetic torque rods dump excess momentum from the wheels, a magnetometer is used to sense the local magnetic field. Sun sensors are also incorporated to help the spacecraft assume a sun-safe attitude if necessary without requiring the relatively power-hungry star tracker.

The STPSat-1 spacecraft has a high power density. Deployed solar panels are needed to provide sufficient area for power generation. High efficiency triple-junction Gallium Arsenide (GaAs) solar cells maximize power generation over the available area. High power density batteries using Lithium Ion technology allow operation through eclipse with a mass much less than older cell technologies. The power handling system is

built into the Integrated Electronics Module (IEM) to regulate and condition power coming off the arrays and shunt excess power to maintain the bus voltage within its specified range.

A solid-state mass memory on a single VME card is used to store payload data for downlink to the ground. Payload data sent to the processor at differing data rates may arrive simultaneously from each experiment. First-In-First-Out (FIFO) buffers offload some of the data collection burden from the processor, lowering processor loading (as compared to per-byte interrupt request system). The processor must be able to sustain a 1 Mbps data stream to the SGLS-compatible transponder for downlink to the ground. The relatively large volume of payload data requires a 1 Mbps downlink rate given the limited ground station contact time available.

The spacecraft must also accommodate stringent payload environmental needs. This not only includes the launch environment, but the thermal and electromagnetic environment during on-orbit operations. SHIMMER contains a CCD imager that uses a Thermo-Electric Cooler (TEC), requiring the spacecraft to provide a dedicated radiator. SHIMMER's optics are sensitive to thermal expansion of the supporting structure, requiring the spacecraft to maintain stringent (± 0.3 degrees C) thermal control of the SHIMMER optical assembly. Contamination of the SHIMMER optics is also a concern that drives the spacecraft materials selection.

The challenge of integrating four widely differing science payloads onto a single compact bus (about the size of a two-drawer filing cabinet) and then performing functional testing and checkout has led to a bus configuration with a separate avionics module and payload module. Splitting the structure into two functional units allows greater access when installing payloads,

and separate build-up of the spacecraft avionics. The modular design also lends greater flexibility for accommodating future missions.

Designing to Interfaces

Launch Vehicle

STPSat-1 is the one satellite on MLV-05 over which the STP organization has direct and complete control. Accordingly, STPSat-1 is being driven to achieve initial launch capability as early as possible. Currently, STPSat-1 expects to spend about a year in storage. It is STP's intent to ensure that STPSat-1 will meet the launch vehicle (LV) schedule with plenty of margin. Of course, there is a price to be paid for being developed so early. The first planned Delta IV launch is only 9 months after award of the STPSat-1 contract, and 2 months after Preliminary Design Review. This means that proven launch environment data has not been available for the early stages of the design process.

To compensate for this lack of environmental information, STP has

imposed very conservative stiffness and quasi-static load criteria on STPSat-1; it is anticipated that this will serve to completely envelope potential environments. STPSat-1 is being designed with a minimum 35 Hz fundamental frequency to withstand 10.6 g loads in two axes simultaneously. These requirements were derived from qualification loads used for Delta IV avionics boxes. Although extreme, this has permitted AeroAstro to proceed with design, supporting plans to ensure that STPSat-1 be ready well ahead of launch. Figure 11 shows a comparison of the typical Delta IV loads envelope versus the current design loads envelope for STPSat-1.

A "mini coupled loads analysis" has been performed with rudimentary information. The analysis started before the award of the STPSat-1 contract, therefore STPSat-1 was modeled as a 181 kg mass at the maximum allowable center of gravity (CG) displacement from the interface plane. An updated CLA is expected in the fall of 2002.

STPSat-1 is constrained to a maximum mass of 170 kg and a static envelope of 60.9 cm x 60.9 cm x 96.5 cm (STP holds 11 kg of mass as a launch reserve; the actual launch capability is

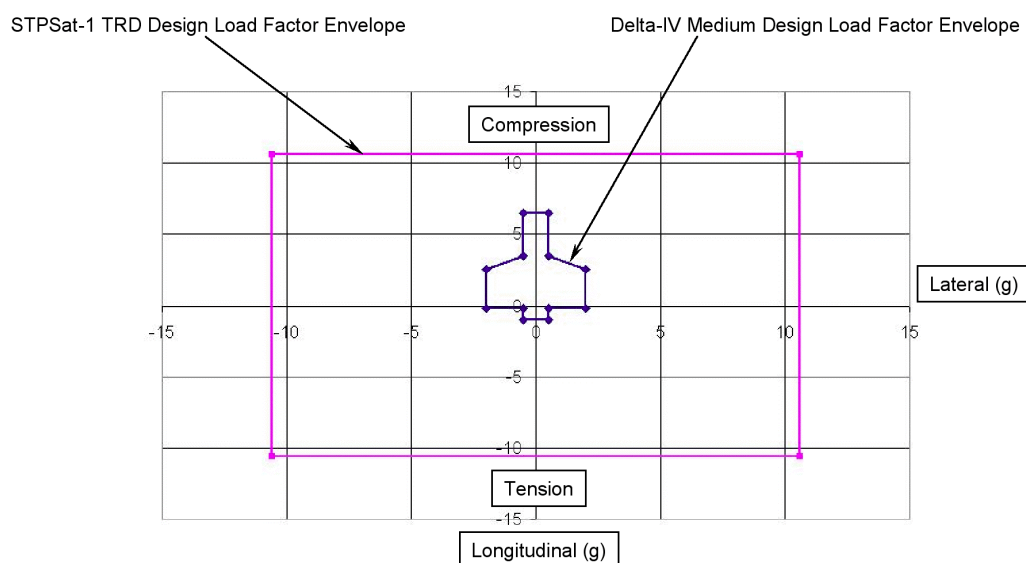


Figure 11. Delta IV-M Loads Compared to STPSat-1 Design Loads

181 kg). The CG of the SV is constrained to less than 48 cm from the ESPA-to-SV interface plane and less than 1.27 cm from the centerline. The ESPA standard interface is a 38.1 cm diameter flange. STPSat-1 will attach to the ESPA using a Lightband separation system provided by Planetary Systems Corporation. The load for the band and the energy for each separation spring is as-yet undetermined, pending detailed analysis.

Electrical connections between the SV, LV, and ground blockhouse are also still undetermined, awaiting selection of the LV Integrating Contractor. Since STPSat-1 will be unpowered throughout ascent, the only anticipated electrical connection to the LV itself is the separation loopback. On the ground, approximately 30 wires will need to connect via umbilical to the SV. Whether these circuits can be passed through the standard EELV umbilical or via some other connection also remains to be determined.

Ground System

STP often uses Det 12/VO to operate SVs that STP procures, as well as to provide planning, resource scheduling, and orbital analysis. Det 12/VO operates and maintains the Research, Development, Test, and Evaluation (RDT&E) Support Complex (RSC) at Kirtland Air Force Base. The RSC provides a link to the Air Force Satellite Control Network (AFSCN). Use of the AFSCN requires STPSat-1 to be Space-to-Ground Link System (SGLS)-compatible, with an appropriate transceiver, data rate, and data format.

The AFSCN schedules resources using a priority system. Operational systems generally have priority over research and development (R&D) satellites, therefore, STPSat-1 can expect to get about half of its

requested time on AFSCN resources and can be removed from the schedule on any given pass for a higher priority mission. Combined with the fact that the RSC will be controlling the three-vehicle AFRL TechSat-21 (in the same orbit as STPSat-1), this requires STPSat-1 to be capable of transmitting all of its daily data in just thirty-five minutes per day (scheduled as four to six daily passes, eight to twelve minutes per pass).

Operations Concept

In addition to designing to an existing ground network (the AFSCN), STPSat-1 is also designed to interface with the RSC, an established command and control facility that operates many USAF satellites. Because multiple payloads will be deployed on MLV-05 and simultaneously controlled by the RSC (three TechSat-21 vehicles and STPSat-1), STPSat-1 is designed to be operationally simple and low risk.

There is a requirement that the SV be capable of autonomous operation for the first 48 hours after LV separation. AeroAstro has implemented design features that address this requirement and the general goal of operational simplicity, including: a completely autonomous deployment and initialization sequence that results in a sun-pointing, power positive and thermally safe vehicle; scheduled commands to turn the SGLS transmitter on for the first 5+ expected passes, and; a system design that turns the transmitter on for two minutes if the SV is radiated by an S-tone modulated carrier (without the need for a command to be received and processed by the vehicle). This reduces the risk of delay in vehicle acquisition in the event of an off-nominal orbit insertion. The RSC plans to use this feature to locate the three TechSat-21 vehicles (as well as STPSat-1) for initial acquisitions, as they are expected to remain in the same antenna beamwidth for several weeks after launch.

Other "operator friendly" features of STPSat-1 include: autonomous entry into safe-hold modes, including safing and power-down of experiments and shedding of non-critical loads; multiple layers of watchdog timers to compensate for potential single-event effects and other anomalies, and; storage of key system parameters that will allow the spacecraft to "fly through" a single-event upset on the flight processor without loss of data or degradation of pointing accuracy.

For nominal operations, the payloads and spacecraft systems are designed so that operations sequences are largely preplanned and controlled almost entirely by stored command sequences, with minimal realtime commanding requirements. This allows greater pass scheduling flexibility and a more relaxed operational tempo, commensurate with the lower operational priority of R&D missions within the RSC and AFSCN.

Incorporating New Technologies

As highlighted previously, STPSat-1 is highly constrained by a number of factors, some of which can be alleviated by using new technologies. In the interest of minimizing risk, however, the team has carefully weighed the advantages and disadvantages before incorporating such technologies. There are several areas where mass and power needs have driven the selection of new technologies incorporated into the design at the PDR stage.

AeroAstro has selected a VME-based avionics architecture that allows maximum use of off-the-shelf boards and components in a well-defined data and electrical interface environment. A single avionics chassis, called the Integrated Electronics Module (IEM), contains the majority of the

C&DH and Power subsystem electronics. While the power control and I/O electronics are custom-designed, the flight processor board and the mass memory card are low-cost, off-the-shelf components. There are a variety of VME-based electronics designs available from a number of vendors, and AeroAstro is in the process of finalizing the flight processor board selection at the time of this writing.

In the power system, tight constraints imposed by the launch vehicle envelope and available mass were major drivers in the selection of battery and solar cell technologies. For batteries, AeroAstro selected Lithium Ion cells for their power density, charging simplicity, and commercial availability (more traditional nickel-cadmium or nickel-hydrogen batteries were too large and heavy). For solar cells, AeroAstro is using triple-junction GaAs cells. To keep the solar arrays simple and reliable, highly efficient cells are needed to provide sufficient power in the limited cell area available (STPSat-1 requires at least 200 watts orbit average power at all times). While triple-junction GaAs cells have some limited flight heritage, risks associated with production and cell laydown techniques require close monitoring and selected special testing.

Since STPSat-1 utilizes GPS for both timing and attitude determination and control (ADCS) functions, GPS is a critical element of the design. Several experiments require timing accuracy to 10 ms; STPSat-1 is using GPS as a time reference in place of an extremely accurate (and expensive) oscillator in the C&DH subsystem. The ADCS uses GPS position knowledge in the control loop to provide inertial-to-local attitude transformations for pointing control. Additionally, GPS will be the primary data source for orbit determination by USAF operators instead of SGLS PRN ranging data, which has traditionally been used for this purpose. While the use of GPS in space is far from new, STPSat-1 faces the challenge of

performing these functions with an extremely low cost design. An inexpensive off-the-shelf receiver with no space flight heritage was baselined for PDR, however, AeroAstro is conducting a trade study to determine the optimal GPS receiver selection and antenna configuration given the criticality of GPS to the success of the STPSat-1 mission.

Minimizing Risk

While new technologies are essential to meeting size, power, and performance requirements in some areas, the reliability concerns push the design toward a simple, proven, low-risk approach in other areas. Using off-the-shelf components with previous flight heritage is one way to minimize risk. New developments involve uncertainties in performance, cost, and schedule. Components that have previously flown are known quantities. They can be procured on a fixed-price basis and delivered in shorter times with more reliable delivery dates. With previous on-orbit performance measurements to back up specifications, these components can be incorporated into a spacecraft design with greater confidence that they will meet requirements. Accurate mass, volume, and power data are available much earlier. Flight heritage provides high confidence that a unit will be compatible with launch and on-orbit environments.

STPSat-1 seeks to use heritage components when consistent with cost and performance guidelines. It should be noted that components with flight heritage do not incorporate the latest advances in technology and may not represent the best capability. Flight heritage minimizes risk and reduces the testing that must be performed; these advantages have to be traded against "old technology" arguments

and potentially inferior performance to make a design selection.

Examples of components with flight heritage that were compatible with cost and performance needs of the program include the SGLS transponder, reaction and momentum wheels, torque rods, star tracker, sun sensors, and release mechanisms. The secure SGLS transponder to be used by STPSat-1 is derived from a long design history of SGLS units built by L-3 Communications and has flight heritage on the GeoLITE mission, and is in use on several missions currently preparing for launch. The CT-633 Star Tracker from Ball Aerospace was selected for its flight heritage on the SOAR mission and heritage derived from previous Ball Star Trackers. Additional heritage components include Torque Rods made by Microcosm, a Magnetometer by Billingsley Magnetics that flew on the SNOE mission, AeroAstro sun sensors with flight heritage on two NASA missions, and the QWKNUT release mechanism made by StarSys Research.

Designing to Cost

STPSat-1 is a very cost-constrained program. While the spacecraft must meet minimum criteria with regard to providing payload support, STPSat-1 is essentially a design-to-cost mission, i.e., it is expected that the spacecraft design will be tailored to provide the maximum capability and minimum risk that can be achieved within the \$12M cost envelope. To that end, a number of decisions have been made to reflect this design-to-cost methodology.

The first prominent example of this approach is the use of a non-redundant single-string design topology. The cost of fully redundant systems is not in the cost of the excess hardware alone; there are also costs associated with the systems that monitor performance and allow switching of redundant hardware (whether under autonomous or manual control). The

subsequent increase in complexity also increases test time and costs. While STPSat-1 uses no explicitly redundant subsystems, there is selected redundancy within the architecture of individual elements. For example, the Lithium Ion battery is composed of three parallel "sub-batteries", any two of which can meet reduced mission needs. This architecture provides robustness without flying a fully redundant battery.

STPSat-1 is also implementing a policy of reduced-cost parts selection. While the use of pure S-class space-qualified parts provides increased reliability, the costs associated with this approach are unsupportable within the constraints of the STPSat-1 budget. The risks inherent in flying purely commercial parts may be considered unacceptably high in proportion to the potential cost savings associated with this approach, however. STPSat-1 has selected to take a middle ground: wherever possible, STPSat-1 will use MIL-883B class electronic components, selecting purely commercial parts only when a significant performance improvement or design simplification is inherent in their selection. It is anticipated that this approach will produce the best tradeoff and help STPSat-1 minimize costs while maximizing reliability.

Another cost-saving approach utilized in STPSat-1 is the design and construction of the structure by utilizing the AeroAstro SpaceFrame structural design concept. This approach uses a simple framework made of off-the-shelf aluminum extrusions to develop a low-risk but sturdy structure with simple load paths. Shear loads and overall stiffness are provided by a combination of machined aluminum and aluminum honeycomb shear panels. While this approach does not necessarily yield an optimized structure, the potential mass

savings of a more complex customized structure are not consistent with the increased development cost of such an approach. The use of SpaceFrame also preserves flexibility to adapt STPSat-1 quickly and easily for different payload complements for future STP programs.

Another cost-saving feature of the STPSat-1 system design is the use of a single processor for all on-board computing tasks. In addition to the raw savings from procuring fewer processors, savings also accrue from reduced power, volume, and mass requirements. Other, subtler cost impacts are attributable to simplified communications and memory architectures that result. A cost savings also results because only a single set of software development tools and systems are required (although multiple copies of these tools are needed due to the number of software developers).

One of the less obvious cost savings resulted from an STPSat-1 build vs. buy trade study. When AeroAstro began to procure the Lithium Ion battery for the space vehicle, it became apparent that the Battery Charge Electronics was a significant cost element associated with the selection of this battery technology. AeroAstro sought to purchase the Lithium Ion battery and associated charge electronics as a bundled system. It was soon realized that this was not an optimal strategy. The preferred battery vendor had no design for the charge electronics and wanted a prohibitive price to develop this unit; the preferred vendor for the charge electronics would only sell the electronics if their battery was selected; a third vendor had no charge electronics and no interest in developing such a capability. A study by AeroAstro showed that a very effective charge electronics design could be developed for a modest cost; this cost could be even further defrayed by sharing the development cost with another AeroAstro program. A decision was made to build this electronics assembly rather

than buy it, and a significant cost savings was passed on to the STPSat-1 program.

Another major cost savings is anticipated to result by making a fundamental change in the Space Vehicle Environmental Test program. At the onset of the program, it was assumed that the spacecraft bus, minus the payloads, would first be environmentally qualified as a stand-alone system. After this test, the payload instruments would be installed and the entire environmental test program would be repeated. AeroAstro has proposed that the stand-alone spacecraft test sequence be eliminated and that the entire space vehicle be tested in a single process. Working closely with the sponsor and their technical advisors, AeroAstro has developed a modified test flow that will protoflight test the entire space vehicle at a substantially reduced cost with only a modest increase in schedule risk; no increase in risk to the space vehicle or payload is expected to result from this change, however, it is anticipated that a cost savings of over 30% of the total test program cost will result.

Conclusion

We introduced this paper by providing an overview of the Space Test Program and the STPSat-1 Space Vehicle (including the STPSat-1 experimental payloads), concluding with a discussion of the MLV-05 launch that will carry STPSat-1 into orbit. We then discussed STPSat-1's unique role as a pathfinder for ESPA launch opportunities. This role causes significant difficulties for STPSat-1 given the dearth of flight environmental data for the EELV, and these difficulties and their accommodations were discussed. The remainder of the paper focused on the constraints and optimization parameters that have shaped the STPSat-1 design, including Payload requirements, LV

interfaces, AFSCN interfaces, and Mission Ops requirements. Each of these interfaces impacts the overall system design in some way, and these impacts were discussed. The last part of the paper focused on how the STPSat-1 design incorporates new technologies when this is enabling, uses existing heritage designs to reduce risk when this is feasible, and remains bound by cost constraints as much as this is possible. This paper demonstrates that this set of constraining interfaces and guidelines, while challenging, is not impossible. A sound spacecraft design has emerged for STPSat-1 that satisfies these many conflicting needs and sets the stage for mission excellence on a budget.

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